

Trace initial interaction from final state observable in relativistic heavy ion collisions

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In order to trace the initial interaction in ultra-relativistic heavy ion collision in all azimuthal directions, two azimuthal multiplicity-correlation patterns — neighboring and fixed-to-arbitrary angular-bin correlation patterns — are suggested. From the simulation of Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV by using the Monte Carlo models RQMD with hadron re-scattering and AMPT with and without string melting, we observe that the correlation patterns change gradually from out-of-plane preferential one to in-plane preferential one when the centrality of collision shifts from central to peripheral, meanwhile the anisotropic collective flow v_2 keeps positive in all cases. This regularity is found to be model and collision energy independent. The physics behind the two opposite trends of correlation patterns, in particular, the presence of out-of-plane correlation patterns at RHIC energy, are discussed.

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The data from current relativistic heavy ion experiments show that a new form of matter — quark-gluon plasma (QGP) has been produced at RHIC [1, 2]. The anisotropic collective flow v_2 is supposed to provide us the information at the early stage of collision. The successful hydrodynamic description [3] on observed mass dependence of v_2 at low transverse-momentum range ($p_T < 2\text{GeV}$) shows that the observed dense matter behaves like a perfect fluid rather than an ideal gas, and is, therefore, referred to as sQGP, although hydrodynamics can still not well fit all the observed data in the range [4]

A complete information about initial interaction and evolution is very important for correctly understanding the properties of the formed matter. The anisotropic collective flow [5] v_2 is the second Fourier coefficient of the transverse-momentum distribution of final state particles. It only globally characterizes the direction and strength of anisotropic distribution. The intrinsic interaction (correlation) of final state particles is absent in the measure.

Another related measure at the market is the 2-particle azimuthal correlation [6, 7]. It concerns the average correlation of two particles separated by a certain angle, no matter where the two particles are in the whole azimuthal space. The 3-particle, or 4-particle, azimuthal correlations focus on the same kind of correlations. How the particles in different azimuthal directions interact with each other can not be drawn from them either.

Newly suggested two spatial-dependent correlation patterns, neighboring and fixed-to-arbitrary bin correlation patterns [8], provide information on how the particles in different cells of phase space are correlated. They measure in the whole phase space the two typical correlations, i.e., correlations between local particles and between particles with a certain distance in phase space. Therefore, they are good observable for tracing the initial interaction among different azimuthal directions in relativistic heavy ion collision.

In this letter, we will first introduce these two cor-

relation patterns into relativistic heavy ion collision. Then, using the Monte Carlo models RQMD [9] and AMPT [10], we demonstrate that the out-of-plane correlation pattern coexists with the in-plane one at RHIC energy, although the anisotropic elliptic flow v_2 keeps positive there. Finally, the physical origin which generates the two opposite correlations — out-of-plane and in-plane preferential correlation patterns is discussed.

It is well-known that the general 2-bin correlation is defined as

$$C_{m_1, m_2} = \frac{\langle n_{m_1} n_{m_2} \rangle}{\langle n_{m_1} \rangle \langle n_{m_2} \rangle} - 1, \quad (1)$$

where m_1 and m_2 are the positions of the two bins in phase space and n_m is the measured content in the m th bin. If there is no correlation between particles in the observed window, C_{m_1, m_2} vanishes.

We divide the 2π azimuthal angle equally into M bins and specify n_m as the multiplicity in the m th angular bin. If we let $m_1 = m$ and $m_2 = m + 1$, C_{m_1, m_2} is reduced to the *neighboring angular-bin correlation pattern*,

$$C_{m, m+1} = \frac{\langle n_m n_{m+1} \rangle}{\langle n_m \rangle \langle n_{m+1} \rangle} - 1. \quad (2)$$

If we fix the position of one bin, $m_1 = m_0$, and vary the left one by m , it becomes the *fixed-to-arbitrary angular-bin correlation pattern*,

$$C_{m_0, m} = \frac{\langle n_{m_0} n_m \rangle}{\langle n_{m_0} \rangle \langle n_m \rangle} - 1. \quad (3)$$

It is clear that these two correlation patterns measure *at various azimuthal positions* how the local particles and the particles separated by a certain angle correlate with each other.

In order to apply these two measures to current relativistic heavy collisions, we choose the RQMD and AMPT models as examples. As we know, the RQMD (relativistic quantum molecular dynamics) with re-scattering is a hadron-based transport model [9]. The

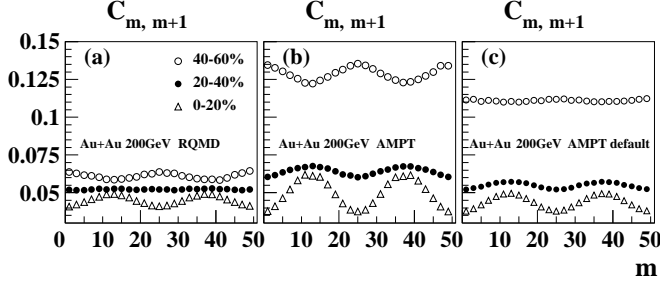


FIG. 1: The centrality dependence of neighboring angular-bin correlation patterns for Au + Au collisions at 200 GeV from the RQMD with re-scattering (first column), AMPT with (second column) and without (third column) string melting.

final hadron interactions are implemented in the model by hadron re-scattering. Although the anisotropic collective flow produced by the model is much smaller than the observed data at RHIC, we can still see how the suggested correlation patterns behave for this kind of transport model.

In contrary to the RQMD model, the AMPT is a "multi-phase" transport model, with hadron and parton interactions both included in. In the default AMPT, the transport in parton level is only partly, and is accompanied by string evolution. While in the AMPT with string melting, the parton level transport is fully taken into account, and reproduces the observed anisotropic collective flow at RHIC [10]. So, using this model we will see how the azimuthal interaction changes when the anisotropic expansion develops from partly to fully.

We generate 249,824, 204,004, and 686,278 events from RQMD and AMPT with and without string melting, respectively. The centrality dependence of neighboring angular-bin multiplicity correlation patterns for Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV are shown in Fig. 1, where the results from the RQMD with re-scattering, from the AMPT with and without string melting are presented in the first to third columns, respectively. As an example, the fixed-to-arbitrary angular-bin multiplicity correlation patterns for Au+Au collisions at the same energy from RQMD with re-scattering are shown in Fig. 2. Here we partition the whole azimuthal range 2π uniformly into 50 equal size angular bins and in the first to third columns of Fig. 2 the positions of the fixed bins are located at $m_0 = 1, 6, 12$, corresponding to the azimuthal angles $\phi \cong 0, \frac{\pi}{4}, \frac{\pi}{2}$, respectively. The errors are statistical only and most of them are smaller than the symbol size in these two and following figures. In this analysis, the $\phi = 0$ refers to the direction of reaction plane in nuclear collisions. In real experimental data analysis, it has to be determined event-by-event.

We can see from Fig. 1 that the RQMD with re-scattering, the AMPT with and without string melting give qualitatively the same centrality dependence of azimuthal correlation patterns. The correlation patterns are $\cos^2 \phi$ like in peripheral collisions, then turn to flat

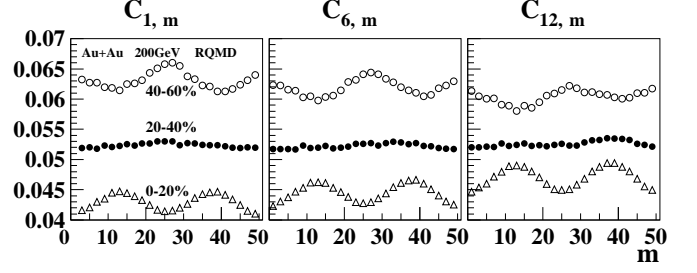


FIG. 2: The centrality dependence of fixed-to-arbitrary angular-bin correlation patterns for Au + Au collisions at 200 GeV from the RQMD with re-scattering.

in mid-central collisions, and become $\sin^2 \phi$ like in near-central collisions. Here, we present only three centrality ranges to show their typical behavior. In fact, the correlation pattern changes gradually from $\cos^2 \phi$ like to $\sin^2 \phi$ like with centrality. In the default AMPT the $\sin^2 \phi$ like pattern is very weak at the centrality 40-60%, and becomes more obvious in more peripheral collision with centrality 60 – 80% (not shown here). It is clear that two opposite trends dominate in peripheral and near-central collisions, respectively. In the mid-central collisions, the two trends turn to balance and the correlations become equal in all directions. Moreover, these important characteristics are independent of the specific assumptions implemented in the three models, in particular independent of the hadronization schemes assumed in these models.

It is interesting and worthwhile to study these two opposite trends in detail. In peripheral collisions, corresponding to the centrality at 40 ~ 60%, both correlation patterns show $\cos^2 \phi$ - like patterns. The strengths of the correlations are the largest at $\phi = 0, \pi, 2\pi$ in neighboring angular-bin correlation pattern and are varying in fixed-to-arbitrary angular correlation pattern — the nearer the fixed angular bin to $\phi = 0$ or π , the larger the correlation strength. It tells us that the final state particles in the directions of in-plane (x - z plane, with z -axis corresponding to the beam direction and x axis along the impact parameter as shown in Fig. 3(a)) have the strongest neighboring correlations, and have also the strongest correlation with the particles in other directions. But the strength of the correlation decreases when the fixed angle goes away from the direction of in-plane as shown in the first to third columns of Fig. 2. These results show that the behavior of particles in in-plane directions has the strongest influence to the behavior of particles in all other azimuthal directions, in contrast with the fixed-to-arbitrary angular-bin correlation patterns in hadron-hadron collisions, where the back-to-back correlations are always the strongest one [11]. These characters are similar to that of in-plane flow resulted from anisotropic expansion, which makes expansion privileged, or correlation stronger, in the directions of in-plane.

On the contrary, approaching to the near-central collision, corresponding to the centrality at 0 ~ 20%, the two correlation patterns show $\sin^2 \phi$ -like patterns. The

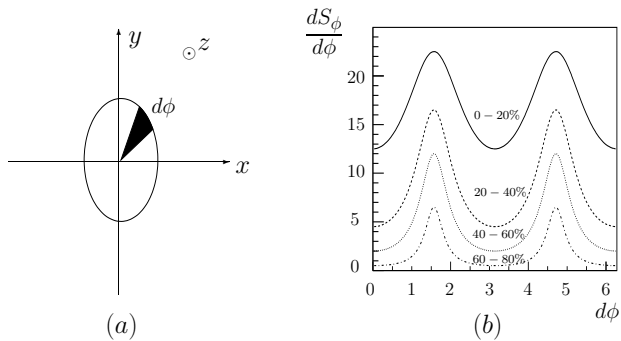


FIG. 3: (a) An angular bin in the overlap zone, which is approximated as an ellipse in coordinate space; (b) The azimuthal distribution of overlap area at four centralities.

strongest correlations are located in both $\frac{\pi}{2}$ and $\frac{3\pi}{2}$, i.e. out-of-plane (y - z plane) directions, instead of 0 and π (in-plane directions), and the particles in the out-of-plane directions have also the strongest correlation with the particles in other directions. It indicates that the behavior of particles in out-of-plane directions has the strongest influence to the behavior of particles in all other azimuthal directions. These characters are opposite to the in-plane flow [5, 12], but are similar to the out-of-plane one, which has been observed at Bevalac and SIS energies [13]. Such an out-of-plane flow was explained as that, before the anisotropic expansion, the participant nucleons, which are compressed in the overlap zone, cannot escape in the reaction plane (x - z) direction due to the presence of the spectator nucleons (squeeze-out effect [14, 15]), producing out-of-plane flow. However, when Lorentz contraction effect becomes significant at ultra-relativistic collisions, the spectators will leave very soon from participant zone [16]. The initial squeeze-out effect is supposed to be hardly realizable at RHIC energies [15]. Therefore, the observed out-of-plane correlation pattern is not due to the initial squeeze-out effect.

It is clear that the anisotropic expansion and the late hadronization are impossible to produce strong correlations in out-of-plane directions. Only the initial source anisotropy is preferential in these directions. The anisotropy of the initial overlap interaction area at non-central collisions results in a larger initial number of participant nucleons in the out-of-plane directions, which in turn generates stronger interaction in these directions.

Let us estimate the azimuthal distribution of participants in the overlap zone and see whether it has the same centrality dependence as the out-of-plane correlation patterns. If we neglect the difference of density in radial direction and approximate the overlap zone as an ellipse, the number of participants should be approximately proportional to the geometrical area of the sector in a given angular bin $d\phi$ as shown in Fig. 3(a), i.e.,

$$\frac{dN_{\text{part}}}{d\phi} \propto \frac{dS_{\phi}}{d\phi} = \frac{1}{2}\rho^2 = \frac{a^2b^2}{2(b^2\sin^2\phi + a^2\cos^2\phi)}, \quad (4)$$

where N_{part} is the number of participant nucleons, S_{ϕ} the overlap area in the angular bin $d\phi$, ρ the radius of the overlap zone in the considered direction. a and b are the semi-major and semi-minor axes of the overlap ellipse and can be deduced from the impact parameter b_{im} and the radius R of colliding nucleus as $a = \sqrt{R^2 - b_{\text{im}}^2/4}$, $b = R - b_{\text{im}}/2$.

In Fig. 3(b), the azimuthal distribution of participants at four centralities are presented. We can see from the figure that the azimuthal distribution of participants indeed behaves similar to $\sin^2\phi$, mimic the neighboring angular bin correlation pattern for near-central collisions shown in Fig. 1. The largest number of participant nucleons are located at $\frac{\pi}{2}$ and $\frac{3\pi}{2}$. The amplitude of the distribution is small in peripheral collisions, increases with the increasing of centrality, and reaches its maximum amplitude at the centrality 20–40%. It goes down slowly with the further increasing of centrality. The amplitude of the distribution will vanish in head on collisions as there is no difference in all directions of overlap area in such collisions. We indeed observed that the correlation patterns tend to flat at very central (centrality at 0–5%) collisions in the AMPT with string melting. Such centrality dependence of the azimuthal distribution of participants can provide us a good understanding in the centrality dependency of the out-of-plane correlation patterns.

The observed correlation patterns present the interactions between the particles in different azimuthal directions. They are resulted from the competition of all kinds of interactions after collision, in particular, the initial interaction and subsequent anisotropic expansion. As long as the system is not fully thermalized, the initial out-of-plane preferential interaction will compete with the subsequent anisotropic expansion. In peripheral collisions, the overlap zone is small and so is the number of participant nucleons, but the difference between the minor and major axes of overlap ellipse is large, and so is the difference of pressure gradient. In this case the anisotropic expansion dominates the final observable, and the effects of initial interaction in correlation patterns are hidden. In near-central collisions, the overlap zone becomes large and the difference between minor and major axes of ellipse is small, so that the initial interactions are strong enough to show themselves up in final observable. This is why the out-of-plane correlation patterns appear at near-central collisions.

Therefore, the azimuthal multiplicity-correlation patterns provide us the information *not only* on the subsequent anisotropic expansion *but also* on the full initial interactions, which are sensitive to the anisotropic shape of initial overlap zone.

We can further see from Fig. 1 that (1) the values of out-of-plane correlation patterns are almost the same in different models; (2) the values of in-plane ones vary greatly from one model to another; (3) the oscillation amplitudes of both the two opposite correlation patterns are the biggest in the AMPT with string melting. The reason of (1) is that the anisotropy of initial interaction

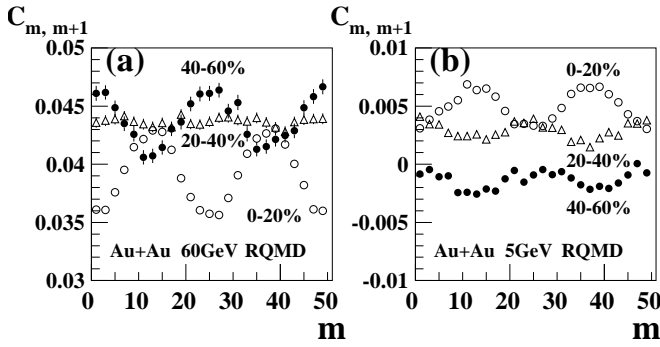


FIG. 4: The centrality dependence of neighboring angular-bin correlation pattern for Au + Au collision at (a) 60 GeV and (b) 5 GeV from the RQMD with re-scattering.

is mainly determined by the geometry of initial interaction zone, which is the same in three models. Meanwhile, the subsequent anisotropic expansion is realized by the late transportation, which is very different in three models, and so are the results of (2). In addition, at the same collision energy, the strength of initial interaction also depends on the interaction mechanism [9, 10]. The anisotropic expansion is built up on the initial out-of-plane preferential interaction. A stronger initial interaction with full transporting results in large correlations in both in-plane and out-of-plane directions, i.e., (3).

In order to see the energy dependence of the correlation pattern, the neighboring angular-bin correlation patterns for Au + Au collisions produced by RQMD with hadron re-scattering at 60 GeV and 5 GeV are shown in Fig. 4(a) and (b) respectively. It is clear that the higher the collision energy, the bigger the values and amplitudes of out-of-plane and in-plane correlation patterns. We can also see from the figure that the presence of out-of-plane and in-plane correlation patterns is independent of collision energy, but dependent on the centrality only.

However, if the initial eccentricity in coordinate space has not been transformed into, or inherited to, the transverse-momentum of final state particles, two oppo-

site correlation patterns will be absent in the final observable. This is the case for RQMD without hadron re-scattering, where the transverse-momentum distribution is isotropic and correlation patterns are flat for all centralities.

As we know, anisotropic collective flow, v_2 , keeps positive in RQMD with re-scattering and in the AMPT with and without string melting at 200 GeV, 60 GeV and 5 GeV, which are in consistent with the corresponding data. The results from the suggested patterns show that even if we observe in-plane preferential transverse-momentum distribution, it does not mean that the correlations, or interactions, have the same preferential directions.

To the summary, we suggest to apply the two azimuthal multiplicity-correlation patterns in ultra-relativistic heavy ion collisions. They are neighboring and fixed-to-arbitrary angular-bin multiplicity-correlation patterns. From the simulation of Au + Au collisions at 200, 60 and 5 GeV by using the MC models RQMD with hadron re-scattering and AMPT with and without string melting, we observe, model and energy independently, that the correlation patterns change gradually from out-of-plane preferential one to in-plane preferential one when the centrality of collision decreases from central to peripheral, while v_2 keeps positive in all cases. The in-plane preferential correlation patterns are resulted by anisotropic expansion, and the out-of-plane ones are found to be likely caused by the initial interaction due to the eccentricity of initial overlap zone. The experimental observation of the out-of-plane correlation patterns predicted in the present letter will offer us a better understanding for the initial pre-thermalization interaction and its competition with the subsequent collective expansion [4, 17] and is, therefore, called for.

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